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## **Do Indoor CO<sub>2</sub> levels directly affect perceived air quality, health, or work performance?**

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This article summarizes the findings of ten recent studies investigating whether increased carbon dioxide (CO<sub>2</sub>) concentrations, with other factors constant, influence perceived air quality, health, or work performance of people.

Concentrations of CO<sub>2</sub> in occupied buildings exceed outdoor concentrations because CO<sub>2</sub> is a product of peoples' metabolism. Indoor CO<sub>2</sub> concentrations are indicators of the rates of building ventilation with outdoor air per person. A higher indoor CO<sub>2</sub> concentration is often considered an indicator of poorer indoor air quality (IAQ), although many factors unrelated to indoor CO<sub>2</sub> concentrations influence IAQ. When indoor CO<sub>2</sub> concentrations increase and decrease, concentrations of other indoor air pollutants emitted from indoor sources, particularly the bioeffluents from humans, may also increase and decrease. Increased indoor CO<sub>2</sub> concentrations have often been associated (correlated) with decreases in perceived air quality, with increases in acute health symptoms, and with reductions in aspects of human performance [1-3]. Research prior to 2012, indicated that levels of CO<sub>2</sub> itself, with other conditions constant, had no significant impacts on peoples' health or performance unless the CO<sub>2</sub> concentrations far exceeded the levels found in buildings [4-10]. The occupational limit for CO<sub>2</sub> in the U.S. is 5,000 ppm for a 40 h work week [11]. Therefore, the previously documented associations of indoor CO<sub>2</sub> concentrations with perceived air quality, health symptoms, and performance have been attributed to the other indoor air pollutants with changes in concentrations indicated by the changes in indoor concentrations of CO<sub>2</sub>.

Since 2012, ten studies [12-23] have investigated whether increases in moderate CO<sub>2</sub> concentrations, with other conditions constant, adversely influence perceptions of indoor air quality, health, or cognitive performance in humans. The study features are described in Table 5 in the IAQScience web site [24]. These studies have been performed with subjects in research facilities enabling CO<sub>2</sub> concentrations to be modified by adding pure CO<sub>2</sub> to indoor air while maintaining all, or nearly all, other conditions constant. By providing high ventilation rates, these studies have maintained low concentrations of bioeffluents. All studies maintained subjects unaware of the CO<sub>2</sub> concentrations. All studies recruited healthy adults, often college-age adults, as subjects. One study employed pilots [16, 21] as subjects, another employed submarine staff [18], and a third employed staff trained as astronauts [20]. All but one of these studies [18] measured changes in perceptual, health, or performance outcomes for each subject, with each subject exposed to multiple CO<sub>2</sub> concentrations. This design eliminated the potential errors that may occur when comparing different groups of subjects. One study [18] employed a study design with three different groups of subjects, each group exposed to a different level of CO<sub>2</sub> in the indoor air. Figures 1-3 depict the major results of this body of research with each horizontal line representing results from a single study or

a part of a study. The circles indicate the CO<sub>2</sub> concentrations employed in the study. A filled in circle indicates a statistically significant (SS) worsening in the outcome at the indicated CO<sub>2</sub> concentration relative to the CO<sub>2</sub> concentration denoted by the left-most circle. The numbers in brackets to the right of each horizontal line indicate the data source.

With respect to subjects' cognitive performance, there are substantial inconsistencies among the results of these experiments. Five studies [12, 13, 16, 17, 20] found SS decreases in aspects of cognitive performance, when CO<sub>2</sub> concentrations were increased and, in some instances, the performance decreases were quite substantial in magnitude. Concentrations of CO<sub>2</sub> as low as approximately 1,000 ppm, relative to 500 to 600 ppm, significantly reduced performance [13, 17]. Four of these five studies [13, 16, 17, 20] employed demanding tests of cognitive performance, either a 90 minute assessment of decision making via a test system called the strategic management simulation (SMS) or a 180 minute test of pilots' performance in flight simulations. One of these studies [20] found a SS reduction in decision making performance at 1200 ppm CO<sub>2</sub> relative to 600 ppm, but performance decreases were not found at 2500 or 5000 ppm CO<sub>2</sub>. Besides assessing performance in decision making, this study also employed a battery of more traditional cognitive performance tests and performance in this battery of tests was generally not affected by CO<sub>2</sub> concentrations. The exception was a general trend toward reduced performance with 1200 ppm CO<sub>2</sub> with the reduction in speed at 1200 ppm being SS. The fourth study [12] found a SS decrease in performance of a proof reading task but not in other tasks, when CO<sub>2</sub> levels were increased to 3,000 ppm, and proof-reading performance decreased only in one of two experiments. Five additional studies [14, 18, 19, 22, 23] found that CO<sub>2</sub> levels had no SS effects on performance. Four of these studies [14, 19, 22, 23] used tests of task performance (e.g., arithmetic tasks, text typing, proof reading, memory) as well as tests of reaction time and attention. In one study, [23], CO<sub>2</sub> levels as high as 5,000 ppm did not influence performance. One of these studies, [19] was conducted at high indoor air temperature of 95°F (35°C) and increased CO<sub>2</sub> did not modify responses attributable to increased temperature. The fourth study [18] found CO<sub>2</sub> levels as high as 15,000 ppm to not affect performance in the SMS test. Overall, among the ten studies, three [13, 16, 17] provide strong evidence of reductions in cognitive performance with increased levels of CO<sub>2</sub>. Two additional studies [12, 20] provide limited evidence of cognitive performance decreases with increased CO<sub>2</sub> levels, but also include evidence of CO<sub>2</sub> not affecting performance. The results of one additional study [22], suggest a possible effect of increased CO<sub>2</sub>. The mechanism by which increased CO<sub>2</sub> concentrations may affect cognitive performance was not clearly identified in any of the studies. A possible explanation is provided by another study [25], albeit one that increased CO<sub>2</sub> levels by restricting ventilation rate per person, hence concentrations of other bioeffluents increased when the CO<sub>2</sub> levels were higher. In this study, as subjects were exposed to levels of CO<sub>2</sub> increasing from approximately 400 to 3000 ppm their forced expiratory volume in 1 second and forced vital capacity decreased. Using models and prior published data, with exposure to higher levels of CO<sub>2</sub>, the authors predicted increases in arterial CO<sub>2</sub> partial pressure and corresponding increases in the bicarbonate content of the blood with a reduction in blood pH. The increased blood bicarbonate and reduction in blood pH was suggested as the explanation for a change in brain functioning when occupants are exposed to higher levels of CO<sub>2</sub>.

Two papers [15, 19] hypothesized that the level of stress associated with the cognitive performance test might explain the discrepancies among findings. Higher CO<sub>2</sub> levels were associated with diminished performance primarily from studies with very demanding, likely stressful, tests of performance. In support of their hypothesis, they found a tendency for subjects to have higher salivary  $\alpha$ -amylase concentrations, suggesting higher mental stress, when CO<sub>2</sub> concentrations were increased. Further support for this hypothesis comes from findings that pilots' performance in flight simulations was reduced when

their heart rate variability indicated a high level of stress [21]. Also, two studies [12, 15] report some increases in blood pressure with exposure to higher CO<sub>2</sub> levels, suggesting higher levels of stress.

The authors of two papers hypothesized that the discrepancies among research findings when subjects took stressful cognitive performance tests was a consequence of the different types of subjects. In one paper [20], the authors suggested that the astronaut-like operations personnel and submariners might have been better able to compensate for effects of elevated CO<sub>2</sub> due to their prior training. The authors of the other paper [18] hypothesized that their subjects (submariners) might have been unaffected by CO<sub>2</sub> as a consequence of their prior regular occupational exposure to CO<sub>2</sub> at 2500 ppm or higher concentrations.

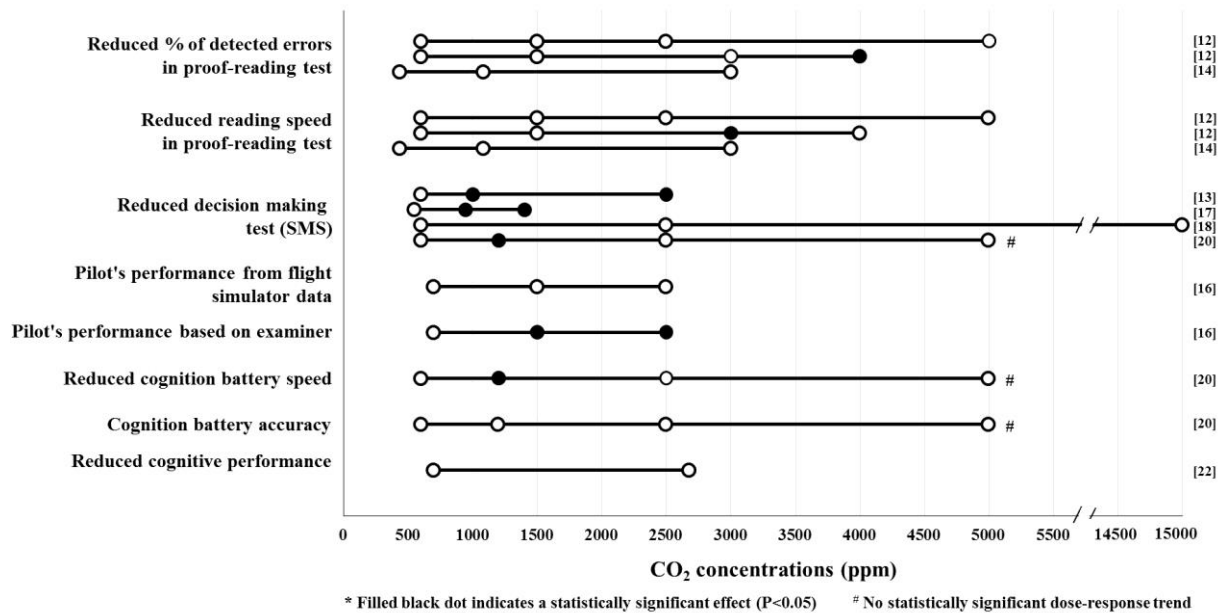


Figure 1. Associations of CO<sub>2</sub> concentrations with cognitive performance.

Five of the studies [12, 14, 18, 19, 23] investigated whether subjects' perceptions of IAQ, e.g., acceptability of indoor air, was influenced by CO<sub>2</sub> concentrations. Only one study [12] found that subjects reported air quality as less acceptable with 3,000 ppm, 4,000 ppm, and 5000 ppm CO<sub>2</sub> relative to 600 ppm.

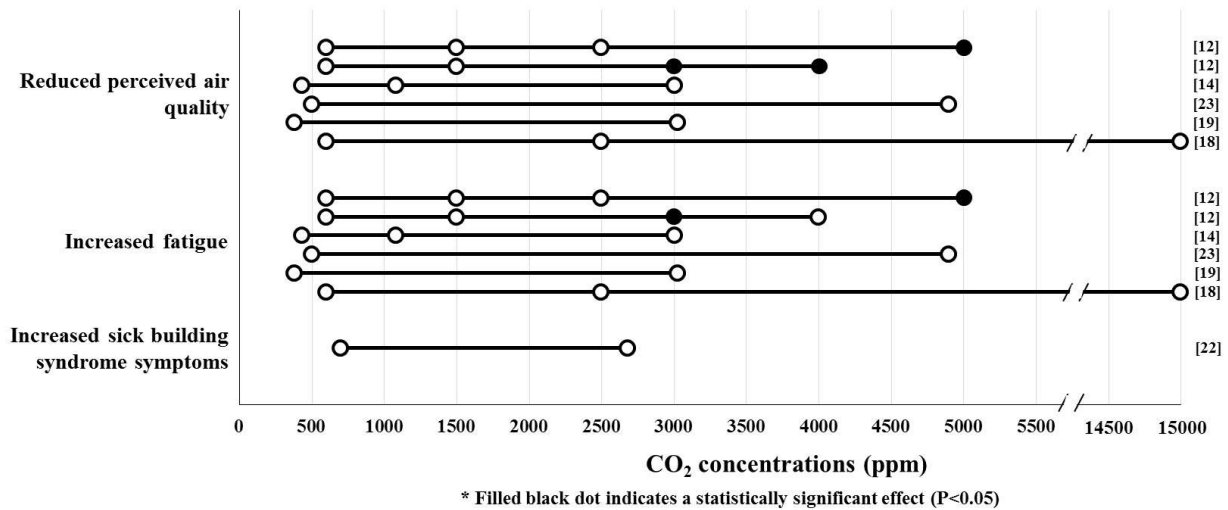


Figure 2. Associations of CO<sub>2</sub> concentrations with perceived outcomes.

Six studies, reported in eight papers, [12, 14, 15, 18, 19, 21-23] investigated whether the level of CO<sub>2</sub> influenced health symptoms reported on questionnaires or health-related physiological outcomes such as blood pressure, pulse, respiration rate, markers of stress, and exhaled concentrations of CO<sub>2</sub>. Four studies that included questionnaires on acute health symptoms [14, 19, 22, 23], including fatigue, found that CO<sub>2</sub> level had no statistically significant effect on symptoms. One study [12] reported that subjects were significantly more tired with 5,000 ppm CO<sub>2</sub> relative to 600 ppm CO<sub>2</sub>. This study [12] also found that blood pressure, respiration rate and volume, and mental effort (based on heart period variability) were increased with higher CO<sub>2</sub> concentrations. In contrast, other studies [15, 19, 23] generally found no statistically significant effects of CO<sub>2</sub> levels on a broad range of physiological outcomes except for increases in the concentrations of CO<sub>2</sub> in exhaled air, called end-tidal CO<sub>2</sub>, and two instances of increases in heart rate. In one study [15], heart rate decreased less during the exposure session with 3,000 ppm CO<sub>2</sub> vs. 500 ppm CO<sub>2</sub> while another study [22] reported a SS increase in heart rate with exposure to 2680 ppm CO<sub>2</sub> relative to 700 ppm CO<sub>2</sub>. Another study [19] found that levels of  $\alpha$ -amylase, markers of mental stress, were higher with 3000 ppm CO<sub>2</sub> compared to 380 ppm CO<sub>2</sub>. Other research [26] has shown that exposure of mice to 2000 and 4000 ppm CO<sub>2</sub> for two hours triggers an inflammatory response and vascular injury with generation of microparticles by immune system cells. Also, in human immune system cells, microparticle generation resulted from increased CO<sub>2</sub> exposures [27].

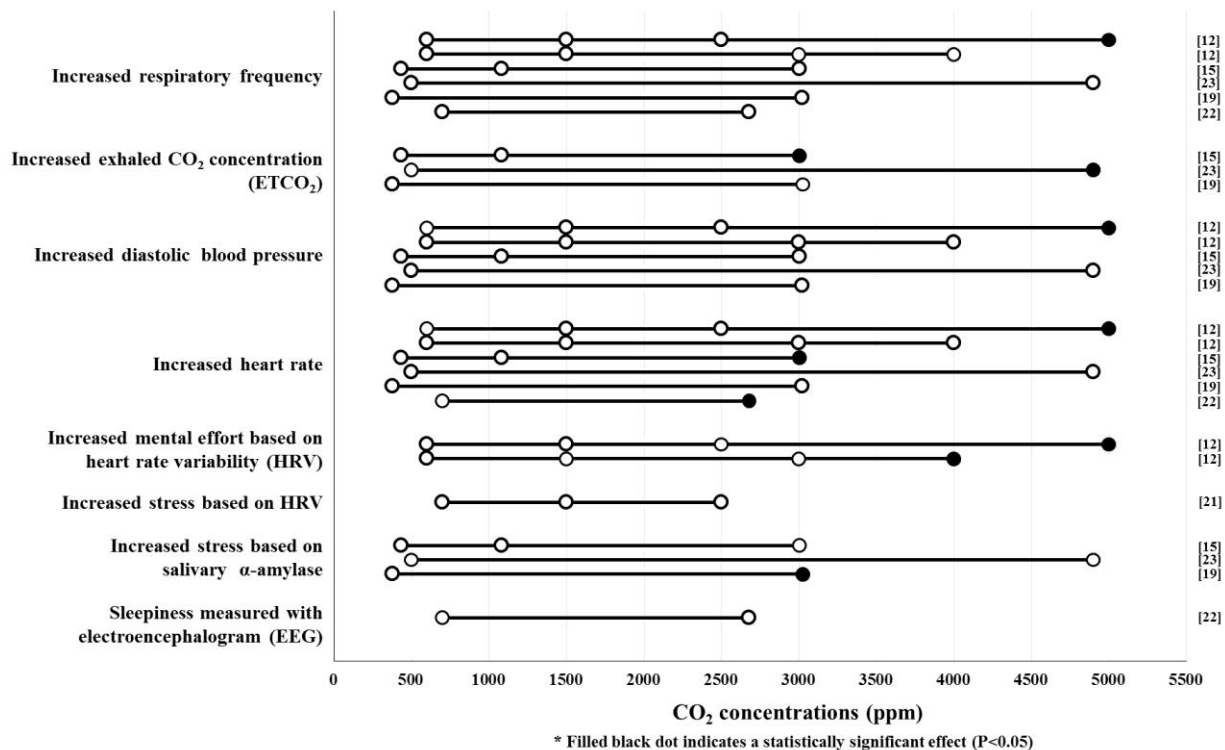


Figure 3. Associations of CO<sub>2</sub> concentrations with physiological outcomes.

The main findings of this body of research are summarized below.

- There is very limited evidence that CO<sub>2</sub> levels below 5,000 ppm influence perceived air quality, acute health symptoms, or physiological outcomes other than end-tidal CO<sub>2</sub> and heart rate. The studies using mice and human immune cells (in vitro) indicate that higher CO<sub>2</sub> levels trigger inflammatory responses, but these findings have not yet been demonstrated in people.
- With respect to acute health symptoms and perceived air quality, the study results, with one exception [12], are consistent and find no effects at CO<sub>2</sub> below 5,000 ppm.
- The results of research on the effects of moderate CO<sub>2</sub> levels on human cognitive performance are not consistent. Some studies find effects of higher CO<sub>2</sub> concentrations on cognitive performance while other studies find no effects on this outcome.
- There is substantial, but still inconsistent, evidence that performance on challenging tests of decision making and challenging flight simulations is worsened by CO<sub>2</sub> concentrations as low as 1,000 ppm. The mechanisms underlying the reductions in performance are unknown.
- Further research is needed to address the discrepancies among the current findings. Additionally, research to date has not investigated the effects of CO<sub>2</sub> on children, the elderly, and people with health problems. Also, the effects of long term continuous or periodic exposures to elevated CO<sub>2</sub> levels has not been investigated. Finally, the extent to which CO<sub>2</sub> mediates the influence of other factors on health or performance requires more research.

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